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HIGGS BOSON PRODUCTION BY VERY HIGH ENERGY NEUTRINOS^{*}

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ABSTRACT

Higgs bosons may be produced by bremsstrahlung off a virtual W^\pm or a Z^0 exchanged in a charged or neutral current neutrino interaction. We calculate the production cross sections and point out that they cannot grow quadratically with E_ν as had been suggested earlier, and argue that at best they can increase like the square of $\ln s/M_{W,Z}^2$ at very high energies. Using a simple approximation for the propagator effect, we present numerical results in the high energy regime $1 \text{ TeV} \leq E_\nu \leq 1000 \text{ TeV}$ appropriate for DUMAND.

I. INTRODUCTION

A truly novel feature of gauge theories is the mechanism by which the symmetry of the original Yang-Mills lagrangian is broken. This is known as the Higgs mechanism, whereby the massless spin one bosons of the original lagrangian are turned into massive intermediate vector bosons W^{\pm} and Z^0 . Higgs bosons are introduced to drive the mechanism, and one is left with at least one physical Higgs boson. This happens, for instance, in the standard Weinberg-Salam model. Equivalently, just as the W^{\pm} and Z^0 bosons are necessary for a renormalizable theory of the interaction of leptons among each other, Higgs bosons are necessary to regulate the interactions of W^{\pm} and Z^0 bosons with each other.¹

The mass of the Higgs boson is not fixed by the theory, but there are arguments² setting a lower bound of about $4 \text{ GeV}/c^2$. As a working hypothesis we shall take $M_H \approx 10\text{-}20 \text{ GeV}/c^2$. More generally, we shall require that $M_H^2/s \ll 1$, where $s = E_{\text{c.m.}}^2$ is the square of the center-of-mass energy. Since we are interested in very high energy neutrinos, this requirement will be satisfied unless M_H is extremely large (for an interesting discussion of this case see ref. 1).

The production of H bosons and their detection by DUMAND has been discussed previously,³ assuming a cross section which increases quadratically with neutrino energy E_ν . Though this is true at low energies, it cannot be true at the high energy regime appropriate for DUMAND. The purpose of this paper is to point this out and make a reasonable estimate as to how the total cross section behaves at high energies. We will argue that σ increases like $\ln^2 E_\nu$ rather than E_ν^2 .

We will discuss in some detail the reaction

$$\nu_\mu + N \rightarrow \mu^- + H + X \quad (i)$$

written symbolically as $\nu_\mu \rightarrow \mu^- H$. The charged current reaction with anti-neutrinos $\bar{\nu}_\mu \rightarrow \mu^+ H$ and the two neutral current reactions $\nu_\mu \rightarrow \nu_\mu H$ and $\bar{\nu}_\mu \rightarrow \bar{\nu}_\mu H$ will be considered briefly and the results will be stated for the standard Weinberg-Salam model only.

II. CALCULATION OF THE TOTAL CROSS SECTION

A basic property of the Higgs boson is that its coupling to a particle is proportional to the mass of that particle. The origin of this property is to be found in the role that Higgs bosons play in gauge theories, namely to generate masses for the vector mesons and fermions in the Yang-Mills lagrangian. It is natural, therefore, to look for H production in a neutrino interaction where a massive W^\pm or Z^0 is exchanged. The Feynman diagram for $\nu_\mu N \rightarrow \mu^- H X$ is:

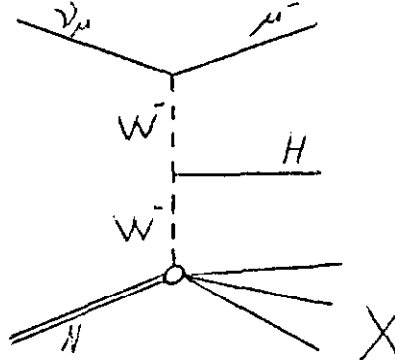


Fig. 1

Other diagrams where the H couples to the muon or a hadron are suppressed because presumably the W^- is the most massive particle in Fig. 1. The $W^- - H - W^-$ vertex is given by the following interaction

$$\mathcal{H}_{\text{int.}} = g_W W_\mu^- W_\mu^+ H. \quad (1)$$

In the standard model, $g_W = eM_W/\sin\theta_W$, where θ_W is the Weinberg angle.

Detailed calculations on reaction (i) based on the Feynman diagram of Fig. 1 have been reported⁴ at low neutrino energies E_ν . In this case each

W propagator can be approximated by $g^{\mu\nu}/M_W^2$, and a simple calculation shows that

$$(\text{Amplitude})_{\mu}^{\nu \rightarrow \mu^- H} = \frac{g_W}{M_W^2} (\text{Amplitude})_{\mu}^{\nu \rightarrow \mu^-} \quad (2)$$

where $(\text{Amplitude})_{\mu}^{\nu \rightarrow \mu^-}$ is the amplitude for deep inelastic scattering $\nu_{\mu} N \rightarrow \mu^- X$.

From Eq. (2) it follows that

$$\sigma(\nu_{\mu} \rightarrow \mu^- H) = \frac{g_W^2}{M_W^4} < \frac{1}{(2\pi)^3} \frac{d^3 p_H}{2E_H} > \sigma(\nu_{\mu} \rightarrow \mu^-) \quad (3)$$

where

$$\sigma(\nu_{\mu} \rightarrow \mu^-) = G^2 s / \pi \quad (4)$$

for deep inelastic scattering off a single quark target, with $s = E_{\text{c.m.}}^2 = 2M_N E_{\nu}$. Note that the linear growth with s or E_{ν} in Eq. (4) is a direct consequence of the assumption $s \ll M_W^2$. If we further assume that $M_H^2 \ll s \ll M_W^2$, then we find⁵

$$\sigma(\nu_{\mu} \rightarrow \mu^- H) = \frac{G^3 s^2}{12\sqrt{2}\pi^3}. \quad (5)$$

We see in Eq. (5) the E_{ν}^2 growth referred to earlier. This is clearly unacceptable behavior in a renormalizable theory. The diagrams that we neglected cannot improve this behavior (as an exercise one can think of the reaction $\nu_e \nu_{\mu} \rightarrow \nu_e H \nu_{\mu}$ where only a diagram like Fig. 1 would be present and the corresponding cross section would also increase with s^2). The cure to this bad behavior is a simple one, and familiar from our experience⁶ with the lower order reaction $\nu_{\mu} N \rightarrow \mu^- X$ where propagator effects reduce the linear growth of $\sigma(\nu_{\mu} \rightarrow \mu^-)$ with E_{ν} into a logarithmic growth.

III. PROPAGATOR EFFECTS

Equations (4) and (5) describe the total cross sections for $\nu_{\mu} \rightarrow \mu^-$ and $\nu_{\mu} \rightarrow \mu^- H$ respectively only in the range $s \ll M_W^2$. The energy range which we

shall consider and which is approximate for DUMAND is $1 \text{ TeV} \leq E_\nu \leq 1000 \text{ TeV}$. For M_W , we will use $M_W = 84 \text{ GeV}/c^2$ which is the value obtained in the Weinberg-Salam model assuming $\sin^2 \theta_W = 0.2$, as indicated by the recent SLAC polarized e-p scattering experiment.⁷ Eqs. (4) and (5) are then valid only for $E_\nu \ll 4 \text{ TeV}$.

To modify our equations in the higher energy regime we use the fact that the total cross section for $\nu_\mu \rightarrow \mu^-$ will increase only logarithmically when the propagator is taken into account.⁶ We will use this as a guide and assume that the same mechanism which turns the linear growth into a logarithmic growth in the case of one propagator will turn a quadratic growth into a doubly logarithmic growth in the case of two propagators like in Fig. 1.

We use the following prescription for taking into account the W-boson propagator effect: replace s in the total cross section by $M_W^2 \ln(1 + s/M_W^2)$. This has the correct behavior both at low energies, $s \ll M_W^2$ and at high energies, $s \gg M_W^2$. For the case of deep inelastic scattering, we have checked that this prescription reproduces the correct results to a good approximation over the whole range of E_ν considered here.

The total cross section for deep inelastic scattering at Fermilab energies can be represented by

$$\sigma(\nu_\mu \rightarrow \mu^-) = 0.6 \left(\frac{E_\nu}{\text{GeV}} \right) \times 10^{-38} \text{ cm}^2. \quad (6)$$

Replacing E_ν by $(M_W^2/2M_N) \ln(1 + s/M_W^2)$ we obtain

$$\sigma(\nu_\mu \rightarrow \mu^-) = 2.3 \times 10^{-35} \ln(1 + s/M_W^2) \text{ cm}^2. \quad (7)$$

This is plotted in Fig. 2. As mentioned above, this is a good approximation to the total cross section over a very large range of neutrino energies. We have checked this by comparing Eq. (7) with

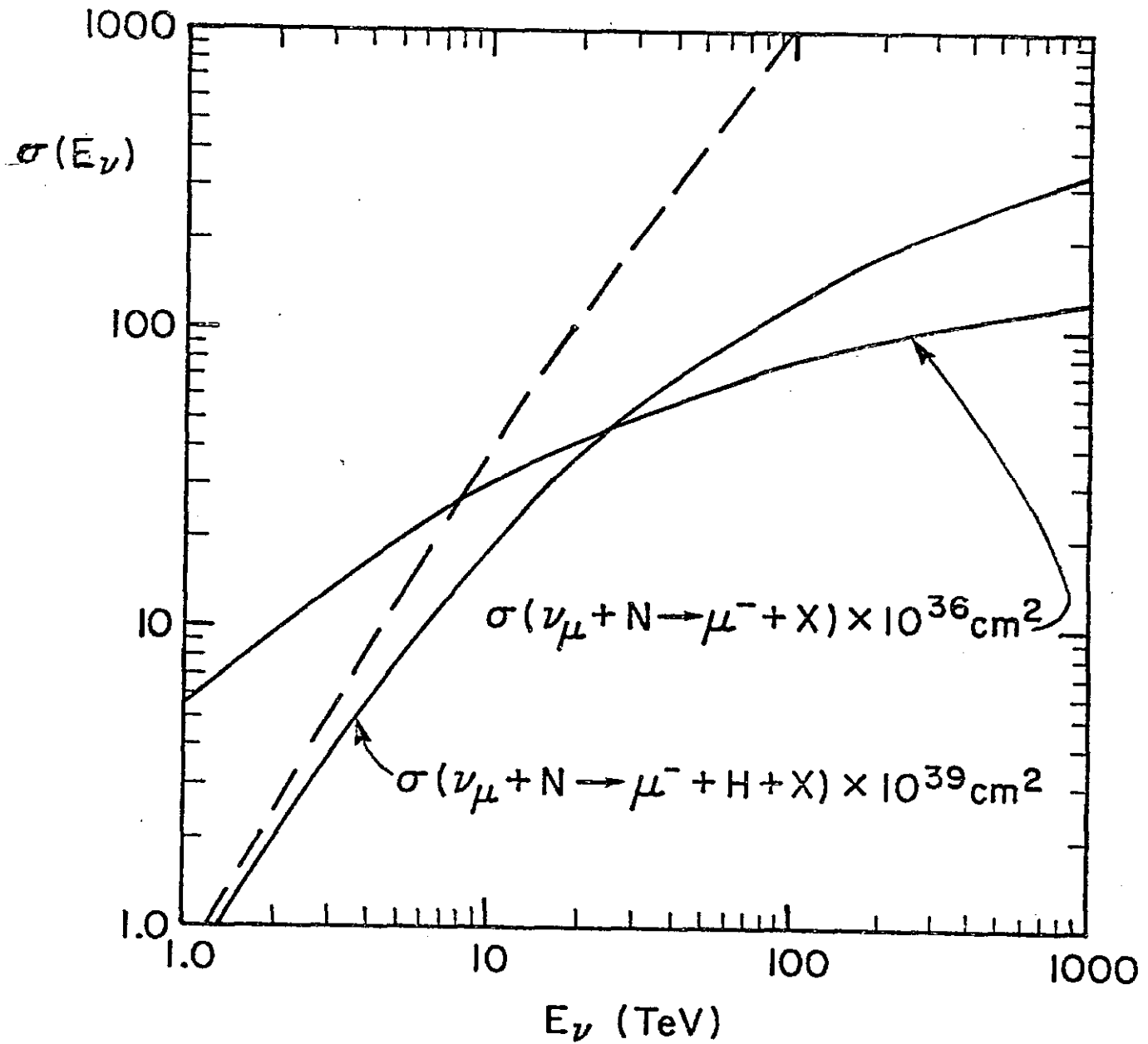


Figure 2

Total cross sections for deep inelastic neutrino scattering $\nu_\mu N \rightarrow \mu^- X$ in units of 10^{-36} cm^2 , and for Higgs boson production $\nu_\mu N \rightarrow \mu^- H X$ in units of 10^{-39} cm^2 . The dashed line is Eq. (9) of the text, with asymptotic behavior $s \log s$.

$$\sigma(\nu_\mu \rightarrow \mu^-) = \iint dx dy (1 + xys/M_W^2)^{-2} \left(\frac{d^2\sigma}{dx dy} \right)_{M_W = \infty} \quad (8)$$

where $(d^2\sigma/dx dy)_{M_W = \infty}$ is the differential cross section for point Fermi interaction, and for which we used the parametrization given by Barger et.al.⁸

We express the Higgs boson production cross section in terms of the deep inelastic scattering cross section. From (4) and (5)

$$\sigma(\nu_\mu \rightarrow \mu^- H) = \frac{Gs}{12\sqrt{2}\pi^2} \sigma(\nu_\mu \rightarrow \mu^-) \quad (9)$$

This quantity is plotted as the dashed curve in Fig. 2. Applying the same prescription, $s \rightarrow M_W^2 \ln(1 + s/M_W^2)$, we obtain what we believe is a reasonable approximation to the actual cross section:

$$\sigma(\nu_\mu \rightarrow \mu^- H) = 1.1 \times 10^{-38} \ln^2(1 + s/M_W^2) \text{ cm}^2 \quad (10)$$

which is also plotted in Fig. 2.

IV. HIGGS BOSON PRODUCTION BY ANTINEUTRINOS

Equations (2) and (3) remain valid for antineutrinos also. The deep inelastic scattering cross section for antineutrinos is given by

$$\sigma(\bar{\nu}_\mu \rightarrow \mu^+) = G^2 s / 3\pi \quad (11)$$

The factor of 1/3 between $\sigma(\bar{\nu}_\mu \rightarrow \mu^+)$ and $\sigma(\nu_\mu \rightarrow \mu^-)$ does not carry over to the Higgs production cross section even though the amplitudes with and without H production are related by a constant g_W/M_W^2 . The reason is that the average over the Higgs boson phase space in Eq. (3) is performed using a different matrix element in each case. A straightforward calculation gives the following result:

$$\sigma(\bar{\nu}_\mu \rightarrow \mu^+ H) = \frac{G^3 s^2}{32\sqrt{2}\pi^3} \quad (12)$$

Combining this with Eq. (5), we find,

$$r \equiv \frac{\sigma(\bar{\nu}_\mu \rightarrow \mu^+ H)}{\sigma(\nu_\mu \rightarrow \mu^- H)} = 3/8 . \quad (13)$$

The equations that we have derived in this section are valid only in the region $M_H^2 \ll s \ll M_W^2$. Again we expect that taking into account W boson propagator effects will turn the s^2 growth in Eq. (12) into $\ln^2 s$ growth in the region $s \gg M_W^2$. We also expect r to remain approximately constant (within a factor of two) as we go to higher and higher energies. Eq. (13) then implies that the total cross section for H production by antineutrinos is about 40% of the corresponding cross section shown in Fig. 2 for neutrinos.

V. HIGGS BOSON PRODUCTION BY NEUTRAL CURRENTS

Higgs bosons may be produced by radiation off a virtual Z^0 interchanged between a neutrino and a quark in a neutral current interaction:

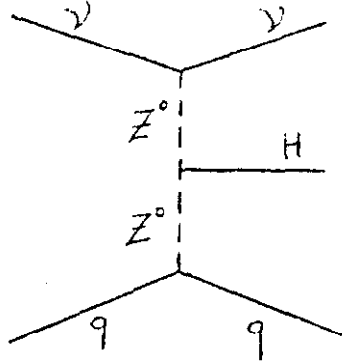


Fig. 3

We will only state the results in the standard Weinberg-Salam model and relate the above neutral current process to the charged current process illustrated in Fig. 1.

$$\sigma(\nu \rightarrow \nu H) = \frac{1}{16} \left\{ \left(1 - \frac{4}{3} \sin^2 \theta_W\right)^2 + r \left(\frac{4}{3} \sin^2 \theta_W\right)^2 \right\} \sigma(\nu_\mu \rightarrow \mu^- H) \quad (14)$$

and

$$\sigma(\bar{\nu} \rightarrow \bar{\nu} H) = \frac{1}{16} \left\{ \left(\frac{4}{3} \sin^2 \theta_W\right)^2 + r \left(1 - \frac{4}{3} \sin^2 \theta_W\right)^2 \right\} \sigma(\nu_\mu \rightarrow \mu^- H) \quad (15)$$

where r is the ratio defined in Eq. (13). In the above two equations, we have assumed a u-quark target. For a d-quark, replace $\frac{4}{3} \sin^2 \theta_W$ by $\frac{2}{3} \sin^2 \theta_W$.

If we choose $r = 0.4$, $\sin^2 \theta_W = 0.2$, we find that

$$\sigma(\nu \rightarrow \nu H) \approx 2\sigma(\bar{\nu} \rightarrow \bar{\nu} H) \approx 0.04 \sigma(\nu_\mu \rightarrow \mu^- H). \quad (16)$$

Therefore, Higgs boson production by neutral currents is only a few percent of the charged current cross section.

VI. CONCLUSIONS

Our main conclusion is that the cross section for Higgs boson production cannot grow quadratically with the neutrino energy, and is much smaller than what this kind of growth predicts it to be. We have made an educated guess as to what the cross section will be, using a prescription which works in the case of one propagator. Our results should be considered as order of magnitude estimates only - detailed calculations are required to get the actual cross section.

In the range $1 \text{ TeV} \leq E_\nu \leq 10^3 \text{ TeV}$, the cross section $\nu_\mu N \rightarrow \mu^- H X$ varies from $6.1 \times 10^{-40} \text{ cm}^2$ to $3.4 \times 10^{-37} \text{ cm}^2$, while the deep inelastic cross section $\nu_\mu N \rightarrow \mu^- X$ varies from $5.4 \times 10^{-36} \text{ cm}^2$ to $1.3 \times 10^{-34} \text{ cm}^2$. Of course, the $\ln^2 s$ growth of the first will eventually take over the second growing only as $\ln s$, but a fantastically high energy is required for this: $\sigma(\nu_\mu \rightarrow \mu^- H) \geq \sigma(\nu_\mu \rightarrow \mu^-)$ only when $\ln s/M_W^2 \geq \frac{12\sqrt{2}\pi^2}{GM_W^2}$, or $E_\nu \geq 10^{923} \text{ eV}$!

We have assumed that the mass of the Higgs boson is smaller than the mass of the W boson. The production of more massive H bosons will be even smaller

than what we have reported here. Since there is no upper bound on M_H , one may wonder what happens if $M_H \gg M_W$. In this case, we again predict that $\sigma(\nu_\mu \rightarrow \mu^- H)$ will grow only like two powers of $\ln s/M_W^2$. The reason is that for the process to be energetically possible we must first have $s \geq M_H^2$, and if $s \geq M_H^2 \gg M_W^2$ then we are already in a region where the propagator effect starts cutting into the cross section. We conclude that our estimates, small as they are, can be considered as upper bounds for $\sigma(\nu_\mu \rightarrow \mu^- H)$ if M_H is large.

The signal for $\nu_\mu N \rightarrow \mu^- H X$ will be a muon accompanied by two hadronic jets.³ One of the jets is from target fragmentation, the other comes from the decay $H \rightarrow \text{hadrons}$. The 3μ signal must be very small because the branching ratio $H \rightarrow \mu^+ \mu^- / H \rightarrow \text{all}$ is small: for example

$$\frac{\Gamma(H \rightarrow \mu^+ \mu^-)}{\Gamma(H \rightarrow c\bar{c})} = \left(\frac{M_\mu}{M_c}\right)^2 \approx 5 \times 10^{-3},$$

reflecting the preference of H bosons to couple to more massive particles.

We have found that other production channels, $\bar{\nu}_\mu \rightarrow \mu^+ H$, $\nu \rightarrow \nu H$, $\bar{\nu} \rightarrow \bar{\nu} H$ are suppressed relative to $\nu_\mu \rightarrow \mu^- H$ by factors 40%, 4% and 2% respectively. From the cross section shown in Fig. 2 for the dominant reaction $\nu_\mu N \rightarrow \mu^- H X$, we estimate that out of one thousand neutrino interactions in DUMAND, only one will be accompanied by a Higgs boson.

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